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# STS Spin-Stabilized Upper Stage Study (Study 2.6) Final Report

## Volume I: Executive Summary

(NASA-CR-145907) STS SPIN-STABILIZED UPPER  
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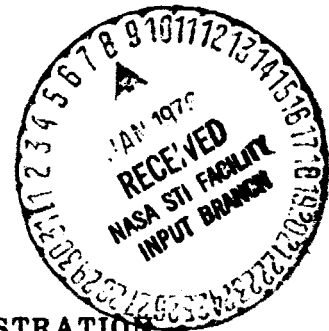
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Prepared by **REQUIREMENTS AND ANALYSIS OFFICE**  
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**Systems Engineering Operations**  
**THE AEROSPACE CORPORATION**

STS SPIN-STABILIZED UPPER STAGE STUDY  
(Study 2.6) FINAL REPORT

Volume I: Executive Summary

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## FOREWORD

This report documents The Aerospace Corporation effort on Study 2.6, STS (Space Transportation System) Spin-Stabilized Upper Stage Study, performed under NASA Contract NASW-2727 during Fiscal Years 1975 and 1976. The Aerospace effort was directed by Mr. W. A. Knittle. Mr. H. E. Gangl, Jr., Marshall Space Flight Center, and Dr. J. W. Wild, NASA Headquarters, were the NASA Study Directors for this study. Their efforts in providing technical direction throughout the duration of the study are greatly appreciated.

This volume is one of two which comprise the Final Report for Study 2.6. The two volumes are:

Volume I: Executive Summary

Volume II: Technical Report

Volume I presents a brief summary of the overall report. It includes the relationship of this study to other NASA efforts, significant results, study limitations, and suggested additional efforts.

Volume II provides a detailed description of the technical effort on the STS Spin-Stabilized Upper Stage Study. It includes a description of the modifications to NASA geosynchronous (non Com/Nav) payloads for spinning injections, sizing and accuracy studies of the spinning stage, resizing recommendations for the total NASA Space Shuttle Upper Stage Mission Model, and safety and operations analyses.

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## CONTENTS

FOREWORD .....	v
ACKNOWLEDGEMENTS .....	vi
1. INTRODUCTION .....	1-1
2. OBJECTIVES .....	2-i
3. RELATIONSHIP TO OTHER NASA EFFORTS .....	3-1
4. SSUS STUDY .....	4-1
4.1 SSUS Concept .....	4-1
4.2 Subtask I: Geosynchronous Payload Model Development .....	4-4
4.3 Subtask II: SSUS Sizing Study and Subtask III: SSUS Applicability to Overall NASA Mission Model .....	4-9
4.3.1 Subtask II Accuracy Analyses/ Design Studies .....	4-13
4.3.2 SSUS System Conceptual Design .....	4-18
4.3.3 SSUS System Cost Estimation .....	4-23
4.3.4 Subtask II Safety Analysis .....	4-25
4.4 Subtask IV: Operations Analysis .....	4-25
5. CONCLUSIONS AND OBSERVATIONS .....	5-1
5.1 Technical Impacts on Satellites .....	5-1
5.2 Cost Impacts on Satellites .....	5-1
5.3 Mission Capture .....	5-2
5.4 Orbit Accuracy .....	5-2
5.5 Design .....	5-3
5.6 Safety .....	5-3
5.7 Flight and Ground Operations .....	5-3
5.8 Cost Estimates in FY 1976 Dollars .....	5-3
5.9 Rockwell International Spinning Solid Upper Stage/ Shuttle Integration Study Conclusions .....	5-4
5.10 Overall Task 2.6 Conclusions .....	5-4

**CONTENTS (Continued)**

<b>6.</b>	<b>STUDY LIMITATIONS . . . . .</b>	<b>6-1</b>
<b>7.</b>	<b>SUGGESTED FUTURE EFFORTS . . . . .</b>	<b>7-1</b>
7.1	System Studies Relating the SSUS Concept to the DOD Solid Propellant IUS Concept Selection . . . . .	7-1
7.2	Dynamic Stability and Injection Error Analyses . . . . .	7-1
7.3	Design Studies . . . . .	7-2
7.4	Operations and Interfaces . . . . .	7-2

## FIGURES

4-1.	SSUS Geosynchronous Ascent Profile . . . . .	4-2
4-2.	Task I NASA Geosynchronous Payloads . . . . .	4-5
4-3.	Planetary Missions Capture . . . . .	4-14
4-4.	EO-09A/SSUS Bay Arrangement . . . . .	4-19
4-5.	EO-57A/SSUS Bay Arrangement . . . . .	4-20
4-6.	Large SSUS Configuration . . . . .	4-21
4-7.	Small SSUS Configuration . . . . .	4-22

## TABLES

4-1	Task I Payload Cost Estimate Summary (Millions of 1975 Dollars) . . . . .	4-7
4-2.	Summary Cost Estimate, $\Delta$ Costs Major System Changes for IUS Expendable to SSUS Spin/Despin Cases (Millions of 1975 Dollars) . . . . .	4-8
4-3.	Geosynchronous Missions Motor Selection Based on Propellant Off-Load Only . . . . .	4-10
4-4.	Solid Motor Characteristics for Geosynchronous Missions . .	4-11
4-5.	Task II Geosynchronous Injection Accuracies . . . . .	4-16
4-6.	EO-57A/SSUS, Delta 2914, and Atlas/Centaur Geosynchronous Transfer Orbit Accuracy Comparison ( $3\sigma$ ) . . . . .	4-17
4-7.	SSUS Cost Summary . . . . .	4-24



## SECTION 1

### INTRODUCTION

The Space Transportation System (STS) will replace the present National Launch Vehicle Family of expendable launch vehicles (ELVs) in the early 1980's for the transportation of satellites and other space payloads. As presently configured, the STS includes a booster stage, an Orbiter, and an upper stage system to be carried within the Orbiter. Utilization of the STS to achieve high-energy orbits is dependent upon the capabilities of the upper stage system provided. The ultimate system will be the full-capability, reusable Space Tug, but it is not scheduled for introduction until 1984.

Prior to the availability of the Space Tug, an Interim Upper Stage (IUS), a modified version of an existing expendable upper stage, will be used. A number of IUS options are presently under study including expendable, reusable, liquid propellant, and solid propellant configurations in several sizes and with varying capabilities and characteristics. However, all of the options being considered feature inertial guidance and three-axis stabilization.

Other alternatives and options to an upper stage system have been postulated. These alternatives generally are satellite or payload provided ("program peculiar") and in some cases may involve simple extensions of major propulsive capability already present in the satellite and the use of inherent satellite navigation and control capabilities to perform the orbit transfers required of an upper stage. One such proposed alternative is an extension of the apogee kick motor (AKM) propulsion system utilized in some satellites for final injection into orbit at the apogee of a transfer orbit. The addition of a perigee kick motor (PKM) propulsion system to inject the satellite into the required transfer orbit has been utilized on ELV boosters and could also be utilized with the STS Orbiter. Thus, a satellite/AKM/PKM system might conceivably avoid the requirement for a general purpose upper

stage system. For simplicity and low cost, satellite/AKM/PKM systems have usually employed spin stabilization. The pursuit of this concept has led to the NASW -2727 Task 2.6 STS Spin-Stabilized Upper Stage (SSUS) Study.

The term Spin-Stabilized Upper Stage is utilized in this report as generic terminology to describe a system deployed from the Orbiter consisting of a PKM and AKM (which may be integral or nonintegral with the satellite) having primary spin stabilization and solid rocket propulsion. The term in some usage may include the satellite, especially where the satellite is the controlling part of the system. The SSUS could also be defined as the PKM system only, referenced to a satellite with an integral AKM system; however, this study task did not specifically include any such situations. The primary propulsion systems involved need not be limited to solid rocket systems, especially in the AKM, but the solid rocket systems were a ground rule element of the study task and liquid systems were not considered.

Due to the SSUS dependence upon the satellite subsystems and the dynamic stability involvement caused by spin stabilization, the SSUS design is a function of the particular satellite design with which it is integrated. The satellites in the NASA mission model encompass the complete spectrum of mission requirements, orbital characteristics, size, and stabilization techniques. The spin-stabilized satellites lend themselves to the SSUS system readily, while the satellites normally operating in a three-axis mode on orbit require extensive modification.

A key element of the SSUS concept is that the Orbiter supplies initial position and pointing guidance and navigation to the SSUS. The Orbiter-SSUS deployment and spin stabilization must maintain these initial conditions so that the subsequent mission events may provide a useful and accurate final satellite orbit. The remainder of the SSUS mission after deployment from the Orbiter and the spin-stabilized PKM injection burn into a transfer orbit is under the command and control of a ground tracking network. The ground tracking network establishes the ephemeris of the transfer orbit; determines the orbital errors and satellite inertial attitude; calculates the required satellite/AKM

attitude, pointing, and apogee velocity vector; and issues the required commands in real time to execute the apogee burn injection into the final orbit with minimum errors.

A large number of potential options, problems, and solutions appeared in the detailed study of the SSUS. Some of these are obvious characteristics, some were appreciated only as they were encountered in the course of study, and some depend upon decisions as to applications. The SSUS appears to be a technically feasible approach for the earth orbit missions, particularly for spin-stabilized satellites. For some three-axis stabilized satellites, the changes required for SSUS integration may be uneconomical. The planetary missions are more difficult and may prove to be impractical for the SSUS. The SSUS is thus an alternative for portions of this mission model if not the entire model, but its economic viability depends on the characteristics and costs of the other STS upper stage options.

During the course of the NASA Task 2.6 study, USAF/SAMSO funded the Rockwell International Space Division on Contract NAS9-14000 CCA 143 to perform a SSUS/Shuttle Integration Study using concept and mass properties data from Task 2.6. The Rockwell International study was reported in Space Division briefing SD75-SH-0165. This study considered the spin-table deployment using Orbiter navigation and stabilization with an auxiliary star tracker mounted on the spin table to deploy a large SSUS from the Orbiter. The results were in general agreement with the Task 2.6 study regarding the feasibility of the concept and provided more detail on the SSUS/Orbiter interface as well as a different approach to spin-table design.

## SECTION 2

### OBJECTIVES

Study 2.6 had two objectives. The first objective was to provide transportation systems and operations data for conceptual designs of spinning solid propellant stages for geosynchronous payloads. This required not only a study of propulsive spinning upper stage systems and their related aspects to perform the geosynchronous missions, but also analysis of selected geosynchronous payloads to evaluate the impact to the payloads of such spinning stages.

The second objective was to review the applicability of these stages to the 1981-1991 NASA Mission Model and determine the subset to which the spinning solid propellant stage is a low-cost alternative to the IUS. Full accomplishment of this objective requires an assessment of the SSUS and IUS on an equal basis which is difficult since the SSUS is a new and relatively undefined system concept while the IUS has had major contracted studies of options evolving successive concepts in considerable depth of detail.

### SECTION 3

#### RELATIONSHIP TO OTHER NASA EFFORTS

The FY 1975 Study 2.6 made extensive use of other NASA-contracted studies and activities. The Space Shuttle Payload Description Activity documents, JSC 07700 Volume XIV, Space Shuttle System Payloads Accommodations, and MSFC 68M00039, Baseline Space Tug, documents were fundamental to the Task 2.6 studies. The IBM IUS/Tug Orbital Operations and Mission Support Study and Martin Marietta Tug Fleet and Ground Operations Schedules and Controls reports were studied for SSUS operations comparisons. Numerous other NASA sources were also contacted formally and informally in the course of the study due to the interrelationship with the entire STS activity.

Considerable advantage was taken of USAF/SAMSO IUS activities in support of the NASA portion of the IUS mission model, and the SR-IUS-100 specification was utilized as representative of a baseline IUS. In addition, a SAMSO-funded Spinning Solid Upper Stage/Shuttle Integration Study, contract NAS9-14000, Rockwell International Space Division, utilized preliminary data from the SSUS Task 2.6 study and provided useful data in return. This study is discussed in greater detail later in this report. In brief, the Rockwell International Study concluded, as does Study 2.6, that spin up of satellites attached to the Orbiter is feasible using a spin table and recommended further study of detail design trades. Advantage was also taken of the five SAMSO-funded IUS studies during the performance of Study 2.6.

## SECTION 4

### SSUS STUDY

#### 4.1 SSUS CONCEPT

The general concept of the SSUS is illustrated in Figure 4-1, SSUS Geosynchronous Ascent Profile. The nominal geosynchronous mission begins with Orbiter injection into a 296.32-km (160-nmi) circular orbit inclined at 28.4 deg. Upon completion of checkout and navigation functions, the satellite and SSUS are deployed in a spin-stabilized mode by the Orbiter with initial position and attitude of the SSUS established by the Orbiter. The deployment system, through use of the Orbiter navigation system augmented with a deployment-system-mounted star sensor, aligns the SSUS with the required perigee velocity vector. After a safe distance retro maneuver by the Orbiter, the SSUS and Orbiter coast in the parking orbit to the appropriate nodal crossing at which time the Orbiter issues a real time arming and firing command sequence through the rf command link to the satellite to fire the SSUS perigee kick motor (PKM) and inject the SSUS into a  $296.32 \times 35,786$  km ( $160 \times 19,323$  nmi) 26.15 deg inclined geosynchronous transfer orbit. Due to the unstable spin inertia to transverse inertia ratios of the SSUS during the parking orbit and transfer orbit coast periods, an active nutation control system must be installed in the satellite to maintain the nutation or coning angle at minimal values between 0.5 and 1.0 deg.

After injection into the geosynchronous transfer orbit the command and control of the SSUS is handed over from the Orbiter to the appropriate ground station network. In this study assumed to be the NASA Space Tracking and Data Network (STDN). The SSUS remains in the 10.5-hour period transfer orbit for several revolutions while the satellite telemetry, tracking, and command (TT&C) link is tracked by the ground station network. The satellite telemetry provides SSUS attitude data from earth and sun sensors mounted on

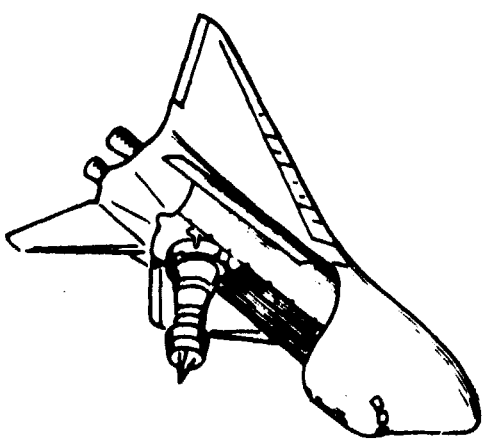
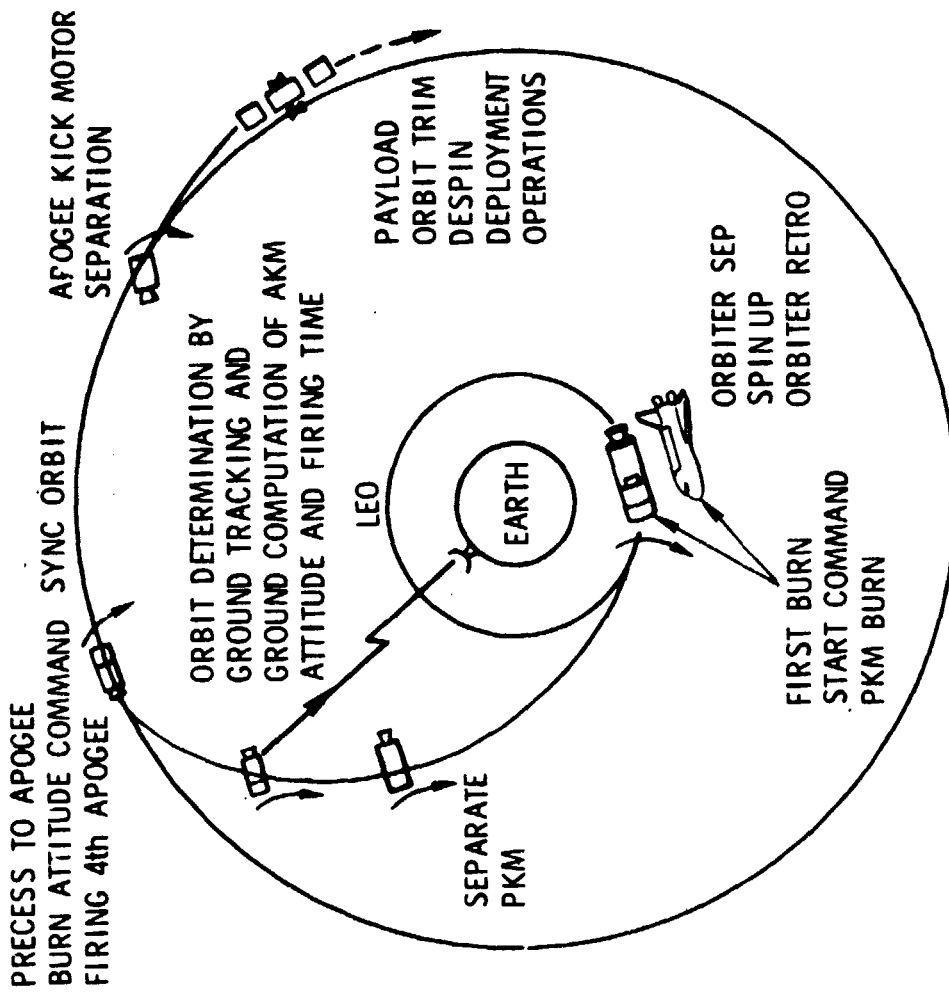


Figure 4-1. SSUS Geosynchronous Ascent Profile

the satellite. Successive coarse and fine attitude correction commands are issued real time to the satellite to precess the SSUS to the desired apogee velocity vector attitude for AKM firing. The ground station network establishes the transfer orbit ephemeris and orbit errors, computes the AKM velocity vector attitude, and designates the time of firing to produce minimum final orbit error after injection. When this has been accomplished (a period of hours or days), the ground station network issues a series of real-time commands to arm and fire the AKM system on the selected apogee (anywhere from the first to the eleventh or later; the fourth apogee is assumed in this study).

After AKM burn and injection into the nominal 35,786-km (19,323-nmi) 0-deg inclined circular geosynchronous equatorial orbit, the ground station network issues a series of commands to initiate normal orbital operations. The actual injection is into a drift orbit with a velocity deficiency, such as 15.24 m/sec (50 ft/sec - 5.5 deg/day) to allow the satellite to be positioned at the final longitude by attitude control system (ACS) thruster firings. The initial commands, after AKM burn, arm and fire the separation system to jettison the AKM stage of the SSUS (may not be required for an internal integrated satellite AKM). Subsequent to AKM jettison, satellite attitude sensor data are evaluated by the ground stations, and commands are issued to precess the satellite to the desired attitude (for spin stabilized geosynchronous satellites, the solar array drum is erected perpendicular to the orbit plane). For satellites which are to be designed to operate on orbit in a three-axis stabilized mode, commands are issued to despin the satellite using satellite tangential ACS thrusters and switch over to three-axis stabilized control. An acquisition sequence is then commanded for the satellite sensors to acquire the earth, sun, and/or stars, depending on the satellite-pointing requirements and reference selections. Commands are issued to deploy solar arrays, antennas, and other stowed satellite empennages.

The ground station network now tracks the satellite to determine the final orbit ephemeris and errors and issues commands for thruster firing to correct the orbit errors, attitude errors, and drift rate. By iterations of



the tracking and orbit adjustments, near-perfect final orbit is achievable with the satellite on final station. These maneuvers require approximately 90 m/sec (300 ft/sec) equivalent delta velocity capability in the satellite ACS system, including approximately 45 m/sec (150 ft/sec) for SSUS injection error correction. For a 362.88-kg (800-lb) satellite, this requires about 13.5 kg (30 lb) of hydrazine ACS propellant out of a total satellite propellant budget of perhaps 27 kg (60 lb) of propellant.

#### 4.2 SUBTASK I: GEOSYNCHRONOUS PAYLOAD MODEL DEVELOPMENT

The seven non-communication/navigation geosynchronous satellites consisted of four designs since the EO-09A Synchronous Earth Observatory Satellite (SEOS), EO-59A, Geosynchronous Earth Observatory Satellite (GERS) and EO-62A, Foreign Synchronous Earth Observatory Satellite (FSEOS) were represented by identical NASA Space Shuttle Payload Description Activity (SSPDA) data and EQ-57A and EO-58A were also represented by identical data. The satellites ranged in SSPDA weight from 1475 kg (3250 lb) to 256 kg (566 lb) and included both three-axis and spin-stabilized design for on-orbit operation. Figure 4-2 illustrates the four basic satellite designs and their major features.

The process of developing a baseline design based on SSPDA (Tug) data consisted of preparation of a basic design layout or sketch to locate major equipments and define features of payload and general arrangement. Subsystem details were developed by preparation of system block diagrams along with identification of required subsystem capabilities and equipments. Mission equipment duty cycles and operations data were utilized in analyzing the subsystems, and in some cases assumptions were required. This process permitted the specification of components and development of weight statements for each subsystem. This was done for each design option matching the upper stage deployment modes. For most satellites, this resulted in four data sets: Tug, IUS, ELV, and SSUS.

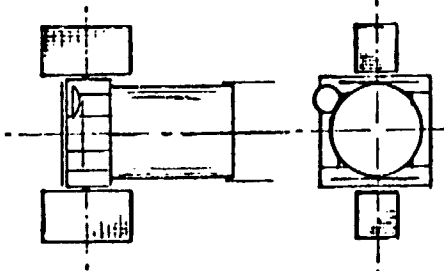
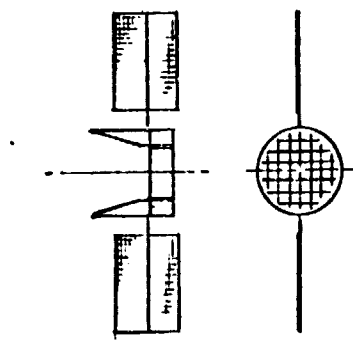
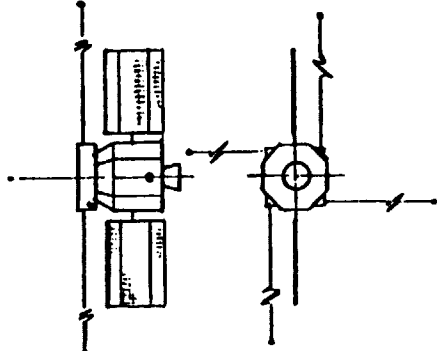
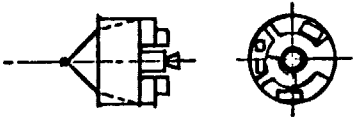
	<b>EO-09A EO-59A EO-62A</b>	<p>Synchronous Earth Observation Satellite</p> <p>1.5-m Cassegrain Telescope</p> <p>1474 kg (3250 lb)</p> <p>3-Axis Stabilized</p>
	<b>EO-07A</b>	<p>Advanced Meteorological Satellite</p> <p>Imaging Radiometer</p> <p>1247 kg (2750 lb)</p> <p>3-Axis Stabilized</p>
	<b>AS-05A</b>	<p>Radio Astronomy Satellite</p> <p>738-ft Cross Dipole Antenna</p> <p>1202 kg (2650 lb) (pair)</p> <p>3-Axis Stabilized</p>
	<b>EO-57A and EO-58A</b>	<p>Meteorological Satellites</p> <p>Visible/IR Radiometer</p> <p>257 kg (566 lb)</p> <p>100-rpm Spin Stabilized</p>

Figure 4-2. Task I NASA Geosynchronous Payloads

11

To the level of detail utilized in these studies, the IUS and ELV configurations were virtually identical. In the case of satellite EO-09A, two extra configurations were analyzed; in addition to the expendable IUS satellite design, an IUS modular design was postulated which could evolve into a Tug modular and serviceable design and a SSUS despun platform design was added to the normal spin/despin SSUS design. The modular IUS design is interesting to compare with the expendable IUS design, as the effects of a modular serviceable design could outweigh the cost effects of the spin/despin modification costs. The SSUS despun platform design was examined to determine the problems encountered should there be an "unspinnable" payload somewhere in the mission model. A despun bearing assembly on the front of the SSUS would permit the payload to have no angular velocity regardless of the SSUS angular velocity. Due to CG offsets, this approach requires added active controls and the despun platform option appears to be an expensive solution to a hypothetical problem.

11

In the process of defining the satellite modifications for the SSUS, sketches were prepared to evaluate equipment locations. These sketches, equipment lists, and weight statements were the basis for the cost estimating procedure for each modification option. The cost estimation process utilized the equipment cost data bank of the modified System/Cost Performance Analysis program for specific equipment and cost estimating relationships for non-equipment items.

The cost estimates are summarized in Tables 4-1 and 4-2. These data indicate that for new design, three-axis-stabilized expendable spacecraft, the SSUS spin/despin deployment option increases the research, development, test and engineering (RDT&E) and unit costs over Tug/IUS/ELV expendable spacecraft designs. The major impacts occur in the stabilization and control and auxiliary (ACS) propulsion subsystems due to the addition of earth and sun sensors, active nutation control systems due to the addition of earth and sun sensors, active nutation control systems, added system functions, additional thrusters, and antennas. These impacts are influenced by the basic spacecraft equipment capability as they determine the degree of modifications required. For the large three-axis

Table 4-1. Task I Payload Cost Estimate Summary (Millions of 1975 Dollars)

SATELLITE	TUG RDT&E Unit	IUS Modular RDT&E Unit	IUS & ELV Expendable RDT&E Unit	SSUS RDT&E Unit	SSUS (Despun) RDT&E Unit
EO-09A	129.7	127.8	124.8	127.0	134.3
EO-59A	47.0	46.6	45.8	46.6	49.8
EO-62A					
EO-57A	27.9	9.68	26.7	26.9	9.63
EO-58A		N/A	9.56		N/A
EO-07A	116.9	44.8	116.9	122.5	46.3
AS-05A	69.6	22.0	69.6	75.1	23.4
		N/A	22.0		N/A

Table 4-2. Summary Cost Estimate,  $\Delta$  Costs Major System Changes for IUS Expendable to SSUS Spin/Despin Cases (Millions of 1975 Dollars)

<u>SUBSYSTEM</u>	<u>AS-05A</u>	<u>EO-07A</u>	<u>EO-09A</u>	<u>EO-57A</u>
Structure	0.1/0.02	0.3/0.10	0.1/0.02	N/C
Electrical Power	<0.1/<0.01	0.1/<0.01	<0.1/0.02	-0.1/-0.06
Communications	0.1/0.04	0.1/0.04	0.1/0.04	0.1/0.04
Stability & Control	3.3/0.98	3.2/0.98	1.4/0.54	N/C
Auxiliary Propulsion	0.8/0.24	0.8/0.26	0.2/0.10	0.2/0.09
Total S/C $\Delta$ Cost*	5.5/1.40	5.6/1.50	2.2/0.80	0.2/0.07

\* Includes GSE, Launch Support, Fee  $\Delta$  Costs

satellites, the RDT E cost increased 2 million to 6 million, and unit spacecraft cost increased \$0.8 million to \$1.5 million. These estimates do not include any impact to mission equipment and assume no cost increase in operations and ground tracking station network costs. Mission equipment RDT&E and unit costs were throughput values for all configurations so that the Table 4-2  $\Delta$  costs are of greater significance than any particular total costs in Table 4-1.

For basic spin-stabilized spacecraft of the EO-57A or SMS/GOES-type, the cost impacts due to the SSUS are small. RDT&E costs increased \$0.2 million and unit spacecraft costs \$0.07 million. The result is as anticipated, since the spin-stabilized spacecraft are basically compatible with the SSUS. In the example of EO-57A, the predecessor SMS/GOES satellite is flown on the Delta 2914 with a spinning PKM and AKM.

#### 4.3 SUBTASK II: SSUS SIZING STUDY AND SUBTASK III: SSUS APPLICABILITY TO OVERALL NASA MISSION MODEL

The SSUS stage sizing was based on the non-communication/navigation geosynchronous payloads, and these analyses were extended as one effort into consideration of resizing for the overall 1981-1991 NASA mission model. All geosynchronous missions were baselined to a 296.32-km (160-nmi) 28.4-deg inclined circular parking orbit for the Orbiter with a geosynchronous transfer orbit perigee velocity requirement of 2.451 km/sec (8042 ft/sec) and an apogee velocity requirement for circularization of 1.779 km/sec (5838 ft/sec). Planetary missions utilized the same parking orbit as geosynchronous missions, and other than geosynchronous earth orbits utilized different Orbiter inclinations where appropriate.

The geosynchronous mission sizing studies indicate that the entire model can be accomplished efficiently with the three existing motors and two new motors utilizing optimum full and off-loaded propellant weights as shown in Tables 4-3 and 4-4. The two new motors could accomplish the entire geosynchronous model, but more efficient packaging of small payloads in the Orbiter bay and less extreme motor off-loading are achieved through

Table 4-3. Geosynchronous Missions Motor Selection Based on Propellant Off-Load Only

	EO-09A	EO-07A	AS-05A	EO-57A
AKM	NM2*	TE-364-4	TE-364-3	TE-M-616
Propellant, kg (lb)	1636.1 (3607)	924.0 (2037)	500.0 (1102)	318.0 (701)
Percent of Off-Load	10	11	23	4
PKM	NM1*	NM1	NM2	NM2
Propellant, kg (lb)	5977.1 (13,177)	3721.8 (8215)	1814.8 (4001)	1261.0 (2780)
Percent of Off-Load	0.6	38	0	31

\*New Motor 2 and New Motor 1

Table 4-4. Solid Motor Characteristics for Geosynchronous Missions

	NM1	NM2	TE-364-4	TE-364-3	TE-M-616
Propellant Weights, kg (lb)	6012.9 (13,256)	1814.8 (4001)	1038.7 (2209)	653.2 (1440)	332.9 (734)
Motor Case Weight, kg (lb)	668.2 (1473)	201.8 (445)	83.0 (183)	64.9 (143)	29.5 (65)
Total Motor Weight, kg (lb)	6681.1 (14,729)	2016.7 (4446)	1121.8 (2473)	718.0 (1583)	362.4 (799)
Propellant I <sub>sp</sub> , sec	292	292	286	290	293
Total Impulse, N-sec (lb-sec)	$1.722 \times 10^7$ ( $3.871 \times 10^6$ )	$5.2 \times 10^6$ ( $1.168 \times 10^6$ )	$2.91 \times 10^6$ (654,400)	$1.860 \times 10^6$ (418,100)	$9.57 \times 10^5$ (215,200)
Thrust, N (lb)	143,448 (32,250)	61,138 (13,745)	68,499 (15,400)	43,146 (9700)	26,688 (6000)
Burn Time, sec	120	85	41	42	35
Propellant Mass Fraction	0.90	0.90	0.926	0.910	0.919



the addition of three existing smaller motors. The new motor No. 1 is used as a perigee kick motor (PKM) with propellant weights from 6009 kg (13,250 lb) to 3719 kg (8200 lb). The new motor No. 2 is used as a PKM with 1814 kg (4000 lb) and 1270 kg (2800 lb) of propellant and as an apogee kick motor (AKM) with 1633 kg (3600 lb) of propellant. The existing TE-M-364-4 and -3 and TE-M-616 motors are used with off-loading as AKMs.

The overall mission model introduces new driver missions. The EO-56A environmental monitoring satellite is in a 1,695-km (915-nmi) circular orbit at 102.97 deg inclination and requires a mission design using three motors to make the plane change at a 5556-km (3000-nmi) high apogee and re-circularize down at 1695 km from an ETR Orbiter launch. The three-stage SSUS required for the EO-56A mission utilizes a first-stage new motor No. 3 with 9070 kg (20,000 lb) of propellant, a second-stage new motor No. 3 with 9070 kg (20,000 lb) of propellant, and a third-stage TE-M-364-4 motor with 1033 kg (2279 lb) of propellant. New motor No. 3 is an additional new motor to the new motors No. 1 and No. 2 identified for the geosynchronous missions. New motor No. 3 is also used in combinations for the planetary missions. Other non-geosynchronous earth orbit missions utilize the existing TE-M-516 with 29 kg (64 lb) propellant and the SVM-3 with a 38-kg (84-lb) propellant motor. Considering the planetary portion of the total mission model, the PL-12A Mariner Jupiter Orbiter and PL-14A Mariner Saturn Orbiter planetary missions are beyond the capture of the SSUS due to the 29,478-kg (65,000-lb) Orbiter limit using present technology motors. Advanced technology motors and more refined structural design assumptions might permit capture of these two missions. The planetary missions can be captured from a propulsive energy standpoint with two- and three-stage SSUS vehicles with the exception of PL-12A and PL-14A missions. A detail mission design sequence, dynamic stability analyses, and error analyses are required before the feasibility of the SSUS for planetary missions can be established. The larger planetary SSUS utilizes new motor No. 3 with 9070 kg (20,000 lb) of propellant as a first stage and another new motor No. 3 with 9070 kg (20,000 lb) of propellant as the second stage. To this two-stage vehicle, a

third stage using the new motor No. 2 with 1814 kg (4000 lb) of propellant is added to capture still higher energy planetary missions. For the lighter weight planetary missions, two-stage vehicles utilizing two new motor No. 1 with 6009 kg (13,250 lb) of propellant and other smaller motors are sufficient and more economical.

Figure 4-3 summarizes the planetary sizing and capture analysis. These capture data are based upon preliminary propulsive stage design studies and are subject to considerable refinement in more detail. Particularly, it should be noted that questions of mission error analyses addressed elsewhere in this study for geosynchronous missions have not been studied for the planetary and non-geosynchronous earth orbit missions.

#### 4.3.1 Subtask II Accuracy Analyses/Design Studies

Orbital error analyses were actually proceeded by a Subtask I preliminary analysis using assumed error sources and SSUS characteristics in order to provide a conservative orbital error correction capability requirement for the Subtask I Geosynchronous Payload Model Development. This preliminary analysis resulted in a satellite orbit velocity correction requirement of 118 m/sec (388 ft/sec), considerably more than current spin-stabilized expendable launch vehicle requirements. More refined Subtask II orbital error analyses were performed later in the study after stage sizing and design characteristics were better defined.

The accuracy studies for the geosynchronous missions were based on Orbiter navigation and pointing capabilities specified in NASA's Volume XIV JSC 07700. The studies indicated that due to the dynamic stability characteristics of the satellites and SSUS, and the basic instability of the system around the required longitudinal spin axis, the orbital error analysis would be a function of each satellite's mass properties and the mass properties of the SSUS employed with each satellite. The accuracy studies were refined to include heading errors provided by analysis of the motor burn dynamics using moment of inertia and mass dissipation during burning, thrust, and CG misalignment and offsets. These studies suggested an increase of spin rate from 30

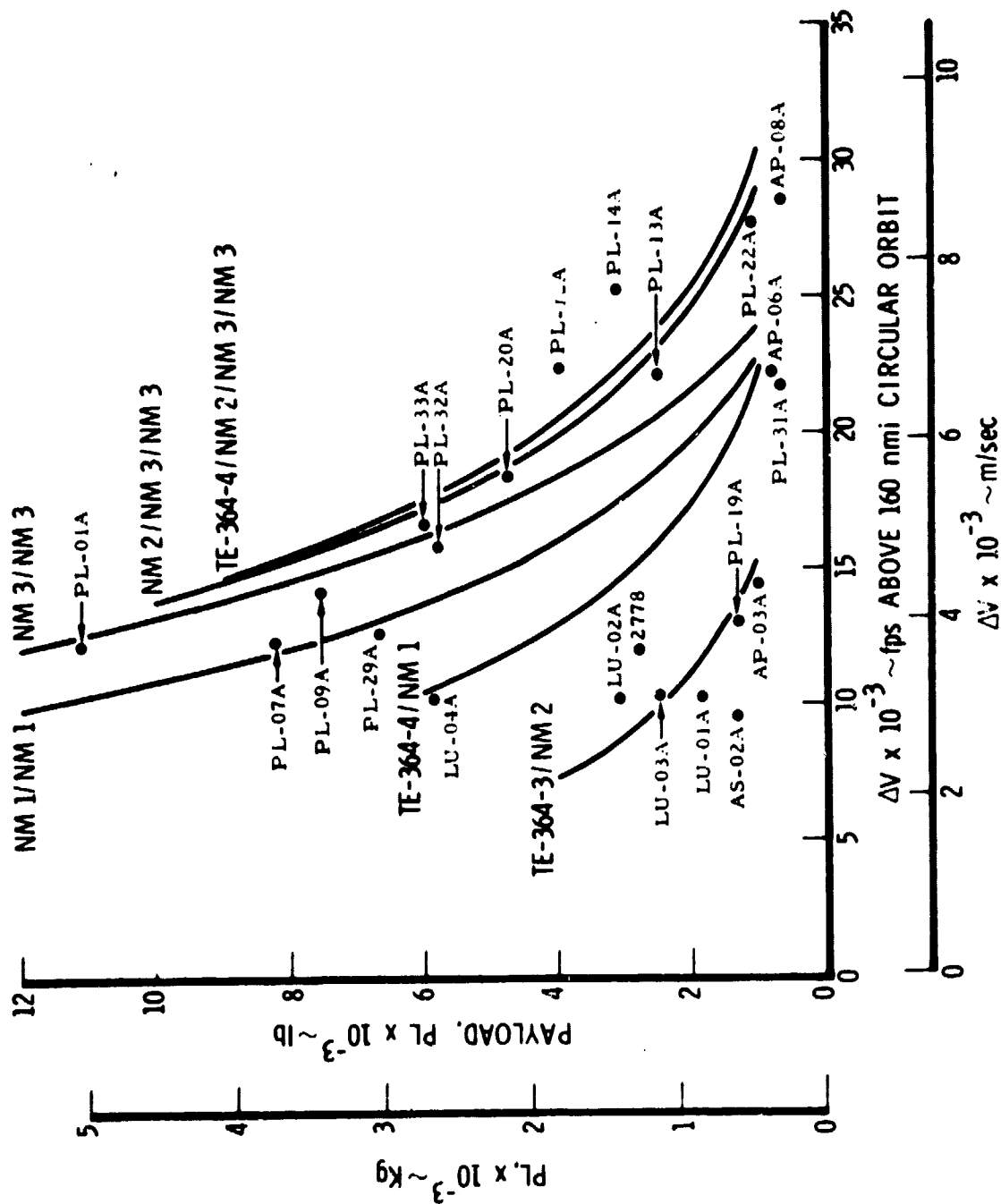


Figure 4-3. Planetary Missions Capture

rpm (assumed for Subtask 1) to 45 rpm for EO-09A, EO-07A, and AS-05A was advisable to reduce heading errors. The 45 rpm represents the approximate 5g lateral load limit for large diameter satellites. Accuracy analysis with EO-57A at 100 rpm indicates the satellite  $\Delta V$  requirement for error correction after AKM burn (biased by ground command to reduce transfer orbit errors) is reduced from the earlier estimates of 118 m/sec (388 ft/sec) to 44 m/sec (145 ft/sec). These data may be compared to the 43 m/sec (141 ft/sec) error correction capability planned for the similar size NATO-III satellite scheduled for Delta 2914 launch in February 1976. Final accuracy computer runs for each satellite were made with the updated error sources.

Table 4-5 compares the final geosynchronous orbit injection accuracies of the EO-57A SSUS system with the SSPDA payload requirements, IUS, and Titan IIC specification requirements. These data indicate the SSUS orbit delta velocity correction capability requirement is approximately twice that of the Titan IIC; i.e., 34.4 m/sec (113 ft/sec) versus 15 m/sec (49 ft/sec) relative to the satellite requirement. This represents the addition of about 3.5 kg (7.5 lb) of hydrazine to the EO-57A satellite. The IUS and Tug guidance systems will have accuracy capability meeting or exceeding the satellite requirements and thus have zero or negative delta velocity data relative to the satellites, permitting the saving of about 7 kg of hydrazine on the EO-57A satellite. Table 4-6 provides a perhaps more realistic SSUS comparison with current spin-stabilized AKM launch vehicle systems. Data are compared for the geosynchronous transfer orbit of the EO-57A/SSUS, the Delta 2914, and Atlas Centaur. These data show very similar accuracy for the EO-57A/SSUS and Delta 2914 presently used for many small satellite spinning injections with AKMs. The Atlas Centaur currently used for Intelsat missions is significantly better due to the use of the Centaur stage for the transfer injection perigee burn with an accurate velocity cutoff rather than the PKM solid rocket employed by the Delta 2914 and SSUS.

Table 4-5. Task II Geosynchronous Injection Accuracies

	Typical Satellite Requirement <sup>1</sup>	IUS <sup>2</sup>	THIC	EO-57A/SSUS	
				3	4
$\Delta V_T$ m/sec (ft/sec)	12.89 (42.3)	4.88 (16)	9.14 (30.0)	35.96 (118)	42.55 (139.6)
$\Delta V_R$ m/sec (ft/sec)	12.89 (42.3)	22.86 (75)	30.48 (100.0)	104.24 (342)	30.48 (100.0)
$\Delta V_N$ m/sec (ft/sec)	17.19 (56.4)	3.66 (12)	24.38 (80.0)	42.67 (140)	28.41 (93.4)
$\Delta P_T$ km (nmi)	46.3 (25)	122.2 (66)	148.2 (80.0)	135.2 (730)	N. A. <sup>5</sup>
$\Delta P_R$ km (nmi)	46.3 (25)	92.6 (50)	129.6 (70.0)	110.2 (595)	107.8 (582.2)
$\Delta P_N$ km (nmi)	62.0 (33.5)	74.1 (40)	83.3 (45.0)	759.3 (410)	9.26 (5.0)
$\Delta V$ (RSS) m/sec (ft/sec)	25.05 (82.2)	23.65 (77.6)	40.08 (131.5)	118.26 (388)	59.59 (195.5)
$\Delta V$ Relative to Satellite Requirement	0	(-1.40) (-4.6)	+14.93 (+49.0)	+93.26 (+306)	+34.44 (+113.0)

<sup>1</sup> SSPDA Data for EO-09A, EO-57A, and EO-07A

<sup>2</sup> SR-IUS-100

<sup>3</sup> Preliminary Data, February 1975, Start Task I w/o AKM Bias Correction

<sup>4</sup> Data, June 1975, with AKM Bias Correction

<sup>5</sup> Not applicable - Payload in 5.5 deg/day drift orbit 15.24 m/sec 50 ft/sec  $\Delta V$

Table 4-6. EO-57A/SSUS, Delta 2914, and Atlas/Centaur Geosynchronous Transfer Orbit Accuracy Comparison ( $3\sigma$ )

Transfer <u>Orbit Deviation</u>	EO-57A/SSUS 296 x 35, 786 Km (160 x 19, 323 nm)	Delta 2914 185 x 35, 786 Km (100 x 19, 323 nm)	Atlas Centaur 185 x 35, 786 Km (100 x 19, 323 nm)
$\Delta H_A$ Km (nm)	1105.6 (597)	1018.6 (550)	250 (135)
$\Delta H_p$ Km (nm)	5.43 (2.93)	7.96 (4.3)	4.63 (2.5)
$\Delta i$ degree	0.107	0.33	0.038

NOTE:

Inclination 26.15°

Atlas/Centaur does not use SRM for Perigee Injection.

#### 4.3.2 SSUS System Conceptual Design

The basic geosynchronous stage and deployment system designs shown in Figures 4-4 and 4-5 consist of large and small two-stage systems using cradles with optional spin tables. The small system features a  $2 \times 2$  Orbiter bay packaging for EO-57A-size payloads. Although the figure shows the  $2 \times 2$  design side by side, Orbiter lateral CG limits for abort with one SSUS still aboard appear to dictate a vertical  $2 \times 2$  design. The basic cradle (possibly the IUS or Tug cradle with adapters) carries all flight loads so that the spin table carries loads only during the erection and spinup. The spin table tilt mechanism elevates the SSUS to clear the Orbiter cargo door hinge line comfortably. The deployment cradle systems provide for options of Orbiter bay spinup to the full 45- and 100-rpm values, partial spin to 5 to 10 rpm with full external spinup by SSUS spin rockets when clear of the Orbiter, and complete spinup external to the Orbiter. In this latter option, the three-axis satellite can maintain stabilization until spinup while a spin-stabilized satellite accepts a random momentum vector pointing which must be pre-processed by Orbiter commands until satellite sensors indicate the desired perigee motor velocity vector pointing is achieved. The unstabilized, random-oriented SSUS concept requires further detailed study to assure that no impact can occur between the Orbiter and SSUS after RMS release and prior to SSUS stabilization and Orbiter retro.

Spin-table and separation system designs progressed to a basic concept of an electric motor drive and explosive bolt with paired spring separation system arrangement. Alternate deployment consists of an IUS-type deployment using the cradle system with the spin table removed and complete external spinup. An alternate stage design was made in which the AKM section has complete electronics, TT&C, ACS, and power systems to perform the injection control and command functions independent of the satellite. This design is in contrast to the basic SSUS concept which is entirely dependent on the satellite and proved considerably more costly. With complete avionics, the SSUS does not appear to be an attractive competitor to three-axis, inertially guided upper stages. The designs shown in Figures 4-6 and 4-7 illustrate the baseline SSUS arrangements with the complete avionics add-on

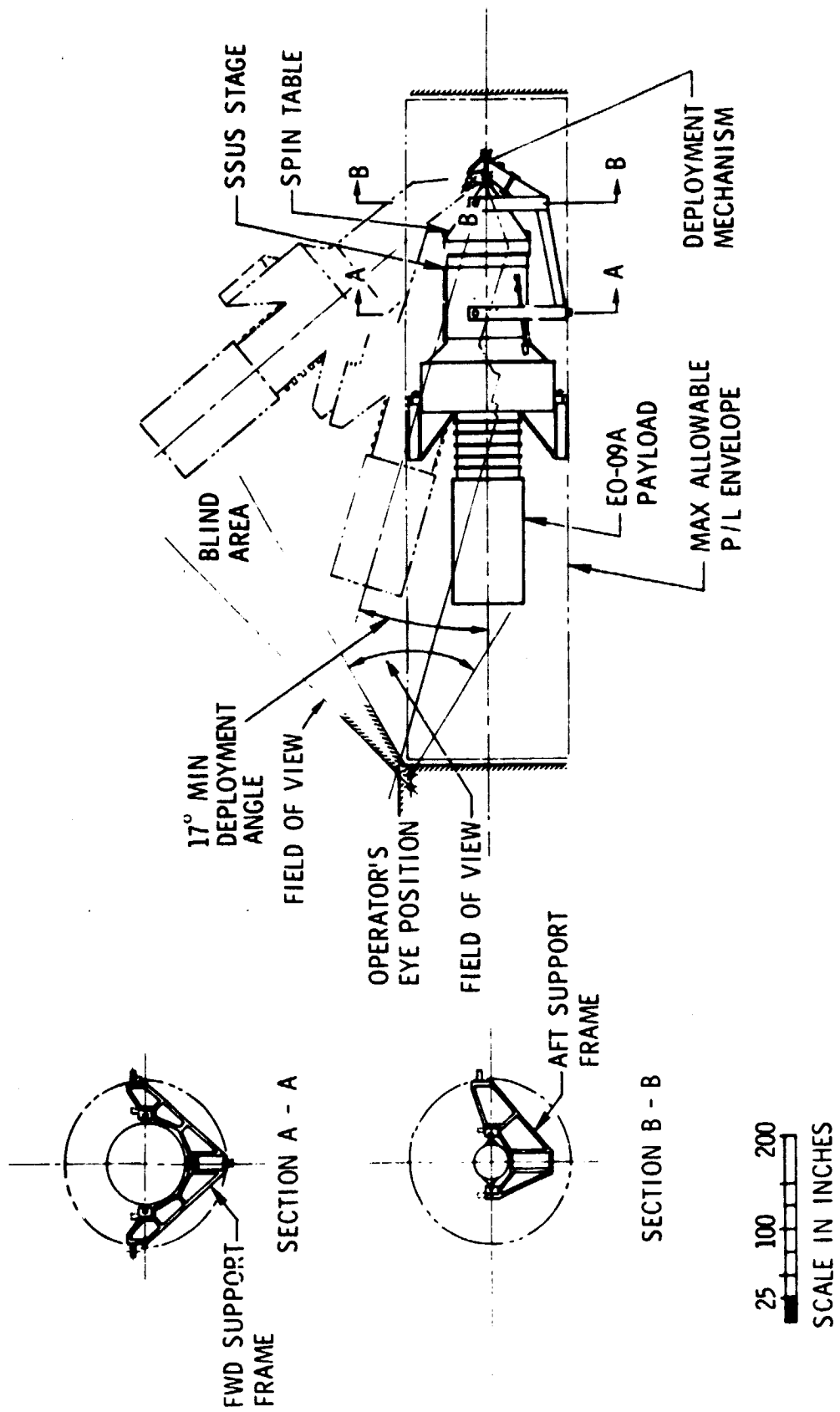


Figure 4-4. EO-09A/SSUS Bay Arrangement



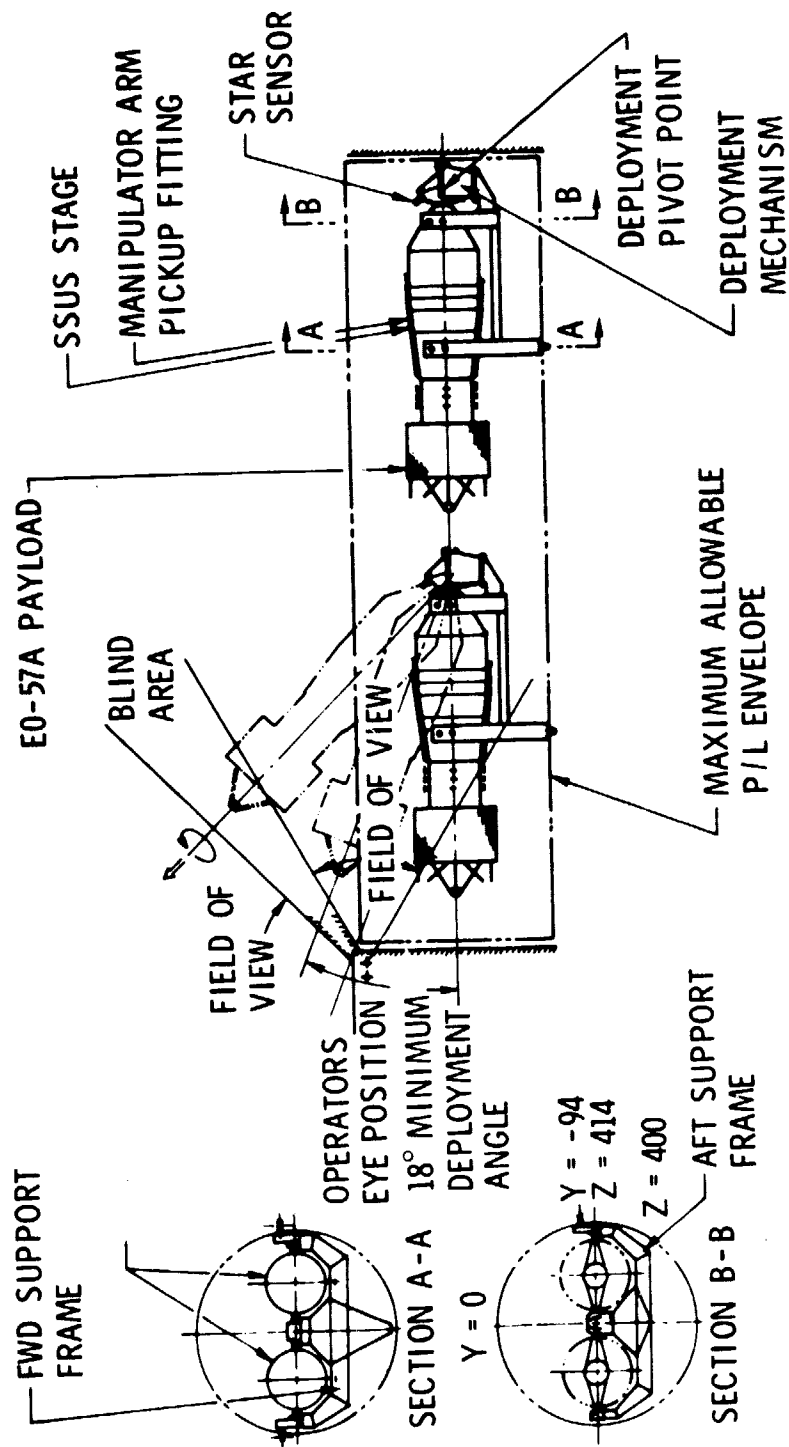


Figure 4-5. EO-57A/SSUS Bay Arrangement

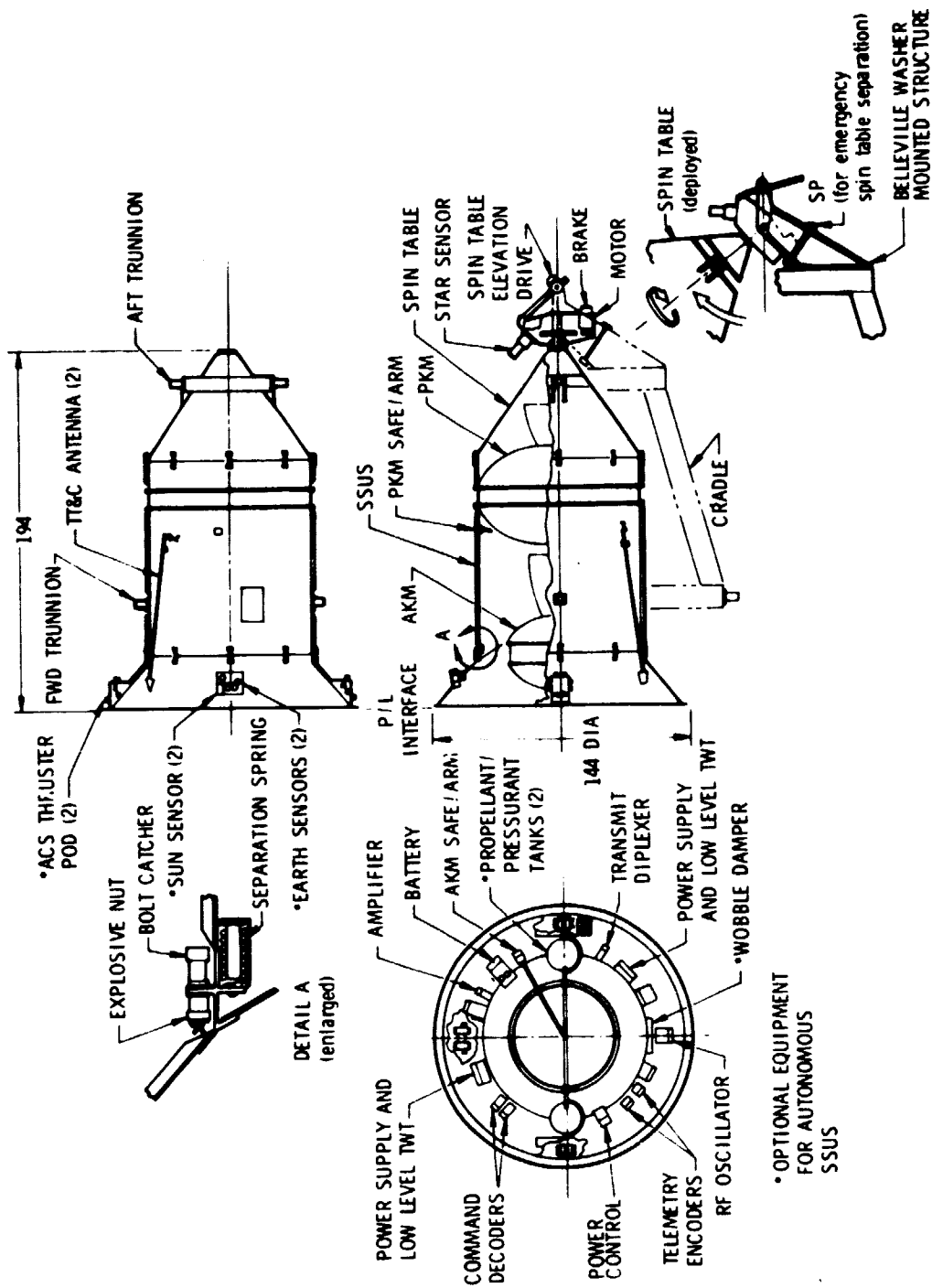


Figure 4-6. Large SSUS Configuration

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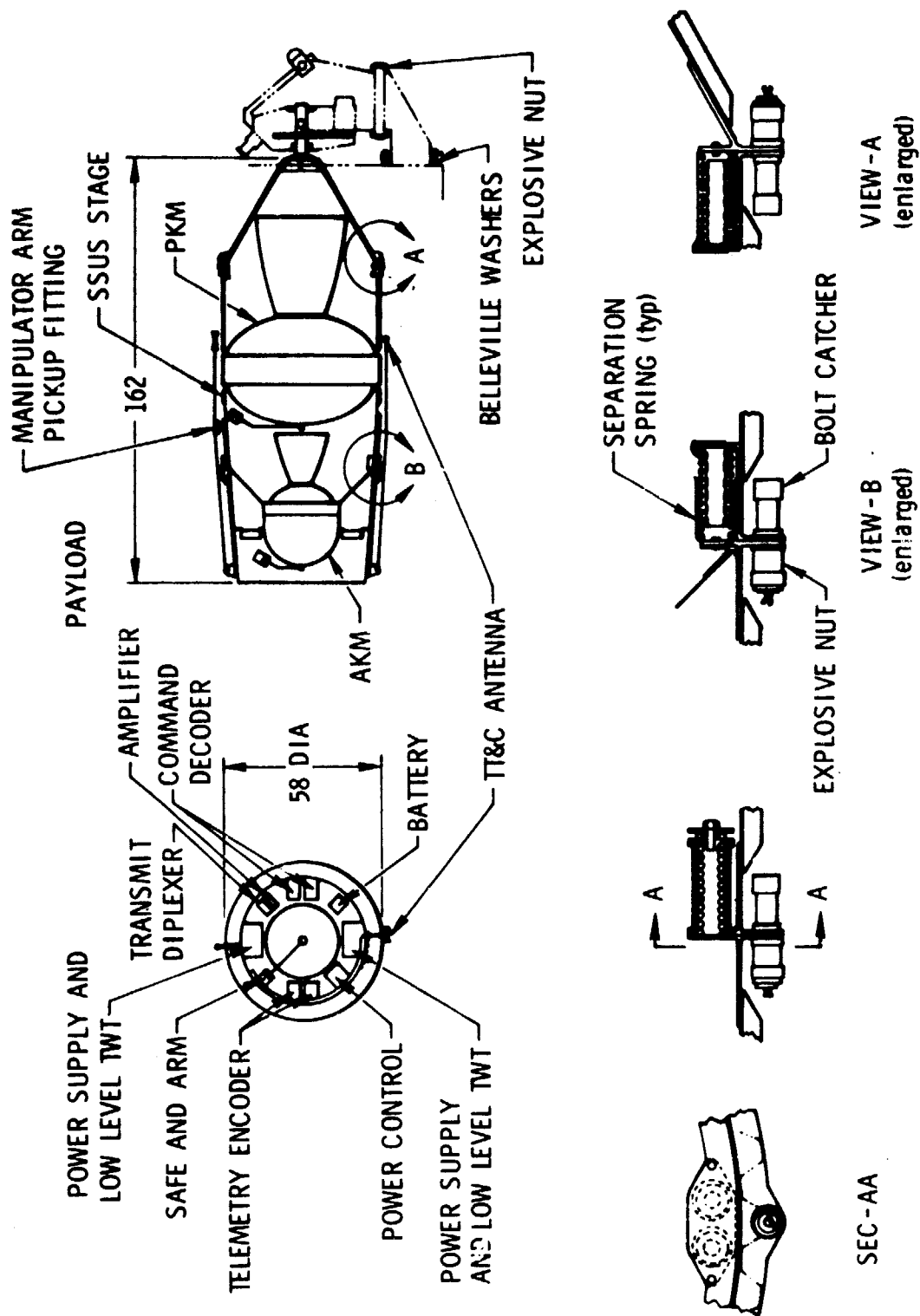


Figure 4-7. Small SSUS Configuration

equipment locations indicated. These SSUS designs are two-stage AKM/PKM arrangements, but they may be utilized as single-stage PKM designs by deletion of the AKM and interstage structure and rearrangement of components for use with spacecraft having integral AKMs.

#### 4.3.3 SSUS System Cost Estimation

The SSUS geosynchronous system cost estimates utilized the cost data bank assembled for the IUS assessment using the same work breakdown structure (WBS) and were done in parallel with IUS cost estimation of essentially the same ground rules where applicable. The depth of detail available in the IUS design assessment was significantly greater than the conceptual SSUS designs. Compensating factors are the simplicity of the SSUS concept, hardware, and operations through use of the satellite features (although at some cost impact to the satellite, Satellite Operations Control Center, and ground tracking network). The adjusted IUS cost data bank WBS elements were utilized with complexity factors to provide SSUS cost estimates.

The SSUS cost elements are presented by options or by building blocks so as to be applicable to portions of the mission model or the total model. Basically, two deployment cradle sizes were costed with spin tables, and two sizes of stage structure and auxiliary hardware are required to match the cradles. Several solid rocket motors are required with full and partial propellant loadings to be used in various combinations in the large and small stages to match the satellite mission requirement. Basic ground and flight operations are essentially identical for all options.

Table 4-7 contains the SSUS cost estimates (less fee) summary for the geosynchronous systems studied. Data are shown for an option covering all geosynchronous missions, an option for small geosynchronous missions only, and for matching autonomous AKM systems and PKM systems only. RDT&E costs include validation, full scale development, and investment providing two sets of airborne support equipment (ASE). Unit costs are shown for buy quantities of 6 and 12 units per year. While RDT&E costs are significant, the unit costs are attractively low relative to the generic IUS and offer possible amortization of the RDT&E depending on detail trade studies, particularly for multiple-mission, small geosynchronous payloads.

Two Stage		Perigee Stage Only	
Geosync. Family	Delta Class	Geosync. Family	Delta Class
EO-09A, EO-07A	EO-57A	EO-09A, EO-07A	EO-57A
AS-05A, EO-57A	Only	AS-05A, EO-57A	Only

Satellite Controlled

RDT&E	\$65.8M		\$35.8M		\$61.3		\$34.1M	
Units/Yr.	6/YR	12/YR	6/YR	12/YR	6/YR	12/YR	6/YR	12/YR
EO-09A	1.05	0.90	---	---	0.68	0.58	---	---
EO-07A	1.00	0.86	---	---	0.65	0.56	---	---
AS-05A	0.95	0.82	---	---	0.61	0.53	---	---
EO-57A	0.81	0.70	0.81	0.70	0.56	0.49	0.56	0.49

Autonomous AKM

Avionics		\$86.9M		\$52.0M		N/A		N/A	
RDT&E	6/YR	12/YR	6/YR	12/YR	6/YR	12/YR	6/YR	12/YR	6/YR
EO-09A	2.62	2.27	---	---	---	---	---	---	---
EO-07A	2.57	2.57	---	---	---	---	---	---	---
AS-05A	2.52	2.19	---	---	---	---	---	---	---
EO-57A	2.38	2.07	2.38	2.07	2.38	2.07	2.38	2.07	2.07

COST FY 76 \$M NO FEE - BASED ON DEVELOPMENT OF ALL MOTORS AND SPECIFIC OFF-LOADED MOTORS REQUIRED FOR EACH CASE

#### **4.3.4    Subtask II Safety Analysis**

The safety analysis review of the SSUS operations and design concepts concentrated on the specific or peculiar hazards introduced by spin stabilization over the hazards common with the IUS/Tug systems. Failure and abort mode considerations influenced the design process. A braking system was suggested for the Orbiter spin table to stop spin and a jettison of a partially tilted SSUS and/or malfunctioned spin table to clear the Orbiter bay and doors was incorporated. Basic hazards appear to be acceptable, compared to liquid upper stage systems, subject to concern on abort landing of the solid stages exceeding 14,515 kg (32,000 lb) weight as they would for some planetary missions.

#### **4.4        SUBTASK IV: OPERATIONS ANALYSIS**

Operations analysis of the IBM and Martin Marietta Corp. IUS/Tug studies were contrasted with conceptual SSUS operations. SSUS basic operations concepts of a system that is satellite-dependent and commanded by a satellite operations control center ground net system differ sharply from the relatively autonomous IUS/Tug concepts. Ground operations are characterized by simplicity and a single major SSUS spin balance, alignment, and assembly facility at the launch site. The spin facility dynamically balances the individual motors and satellites, performs a precise CG alignment and assembly/checkout for each SSUS stack, and installs the SSUS in the deployment cradle and/or spin table. It may be desirable to not only balance the individual masses of satellites and motors but to spin check the entire assembly. From this facility, it would be transported like any other upper stage. The SSUS considered as an addition to the IUS or Tug has no significant impact on the IBM IUS/Tug Orbital Operations and Mission Support Study. The SSUS impacts are primarily in the Orbiter Interface and Flight Operations, the Ground Tracking Network, and the Spacecraft Operations Control Center.

SSUS time lines for the geosynchronous system are relatively long compared to the IUS due to the revolutions in the transfer orbit for ground tracking prior to AKM burn. Tug time lines are comparable if phasing orbit ascent profiles are used. The SSUS orbit accuracy is comparable to present Delta 2914 ELV and has errors approximately 2-1/2 times as great as the IUS/Tug systems. SSUS satellite support is negligible compared to the IUS or Tug; in fact, essentially, the SSUS is supported by the payloads with power, command, and control.

## SECTION 5

### CONCLUSIONS AND OBSERVATIONS

The Task 2.6 study results indicate that the concept of a spin-stabilized solid rocket upper stage for the STS is a technically feasible concept and may be economically viable for a portion of the mission model, depending on the competing system options. Specific conclusions and observations are outlined in the following paragraphs.

#### 5.1 TECHNICAL IMPACTS ON SATELLITES

Requirement for spin-stabilized transfer at 45 to 100 rpm, 5-g centripetal acceleration, symmetry desirable, balance and ballast CG location  $\leq 2.54$  mm (0.1 in.) to spin axis.

Active nutation control system required with 22.24-N (5-lb) thruster control.

Addition of earth and sun sensors for spin functions.

Increased ACS propellants for nutation, precession, despin (of three-axis), and greater orbital errors.

Command interfaces with Orbiter, SSUS, and ground station networks and omni-antenna requirements.

Longer duration missions due to transfer orbit tracking of several revolutions for AKM firing.

Requirement for partial satellite power up and partial power from folded solar arrays.

#### 5.2 COST IMPACTS ON SATELLITES

For new design, three-axis stabilized, expendable spacecraft, spin/despin SSUS increases RDT&E and unit costs compared to Tug, IUS, and launch vehicle expendable designs due to added stabilization and controls, sensors, and functions.



- a. Cost increases \$2.2 million to \$5.6 million RDT&E
- b. Cost increases \$0.8 million to \$1.5 million unit cost

Cost and changes influenced by capability of basic spacecraft equipment.

For spin-stabilized spacecraft such as EO-57A and current SMS/GOES, SSUS design and cost effects are minor.

- a. RDT&E costs increase up to \$0.2 million
- b. Unit costs increase up to \$0.07 million

### 5.3 MISSION CAPTURE

Feasible to capture geosynchronous and other earth orbit missions.

Two new solid rocket motors (1,800 and 6,000 kg) and three existing motors capture geosynchronous missions.

A third new motor (9,000 kg) and two more existing solid rocket motors capture the entire model (except PL-12A and PL-14A) from a propulsion energy standpoint.

Planetary mission capture requires further study in mission design, stability, and accuracy to establish full feasibility.

### 5.4 ORBIT ACCURACY

For geosynchronous missions, SSUS accuracy is equal to present Delta expendable launch vehicle.

SSUS accuracy is inferior to Tug and IUS inertial guidance; SSUS errors are three times greater.

Satellites can correct SSUS injection errors utilizing hydrazine ACS equivalent to slightly more than 2 percent of the satellite weight. Best accuracy is achieved with optimum propellant load solid motors, and optimum  $\Delta V$  trajectory design.

Accuracy and stability intimately related to mass properties, balance, and alignments of spacecraft, AKM, and PKM.

## 5.5 DESIGN

Spin-table deployment with table-mounted star sensors and Orbiter navigation.

Geosynchronous total model can be met with a large 9,000-kg (20,000-lb) gross weight, two-stage system (AKM/PKM) in single or dual (forward and aft) installation and a small 3,200-kg (2,000-lb) gross weight, two-stage system in a  $2 \times 2$  vertical Orbiter bay arrangement (2 forward, 2 aft).

- a. Multiple-payload Orbiter flights utilizing multiple SSUSs
- b. Multiple payloads on a single SSUS are limited due to requirement for CGs to be on spin axis.

## 5.6 SAFETY

Spinning hazards well understood; much history.

Deployment design must incorporate safety considerations, redundancy, fail safe modes, and abort modes.

Thorough dynamic separation analyses required.

Inadvertant motor ignition commands and other hazards similar to any upper stage.

## 5.7 FLIGHT AND GROUND OPERATIONS

Orbiter SSUS cradle/spin table installation simple.

Orbiter RF control of SSUS through PKM burn.

Satellite Operations Control Center/Ground Tracking Station Network control of SSUS from PKM burnout through final orbit insertion.

Time line within established Orbiter/IUS/Tug plans.

Ground operations simple; balance, alignment, and assembly facility similar to present Delta Spin-Balance Facility required.

## 5.8 COST ESTIMATES IN FY 1976 DOLLARS

Delta-class SSUS system development costs for 250- to 500-kg (550- to 1,100-lb) payloads are \$35.8 million, and RDT&E unit costs are \$0.8 million.

Large and small SSUS system for entire Geosynchronous Mission Model with two sizes of spin table costs \$65.8 million for RDT&E; large SSUS unit costs are \$1.05 million and small SSUS unit costs are \$0.8 million.

PKM-only Delta-class SSUS RDT&E costs are \$34.1 million; unit costs are \$0.56 million.

Full avionics option addition to SSUS adds approximately \$20 million RDT&E costs and \$1.6 million per unit to above costs.

#### 5.9 ROCKWELL INTERNATIONAL SPINNING SOLID UPPER STAGE/SHUTTLE INTEGRATION STUDY CONCLUSIONS

Spinup of satellites attached to Orbiter is feasible and can be done safely.

Baseline concept (spin table/cradle/star sensor) is one method to perform task.

id-body spin up is viable option.

Multi-satellite deployment can be accomplished with special designs.

Rough-order-of-magnitude costs are \$8.0 million for spin table, \$7.9 million for cradle, and a \$15.9 million in total FY 1976 dollars.

#### 5.10 OVERALL TASK 2.6 CONCLUSIONS

SSUS concept technically feasible.

SSUS as accurate as Delta.

Appears more attractive for Delta-class payloads portion of the Geosynchronous Mission Model.

## SECTION 6

### STUDY LIMITATIONS

The study was limited in scope to conceptual evaluation at all levels. The development of the geosynchronous payload data was limited by the data and understanding provided in the SSPDA which is an evolving data base itself. Also, due to these limitations, no assessment of the impact to satellite mission equipment was made, although it did seem feasible to spin the types of equipment in the seven satellites studied. However, this may not be true for other types of mission equipment.

The conceptual approach and time limits to both satellite and SSUS design did not involve a level of detail and an examination of all options which would permit selection of optimum designs. Rather, feasible designs were considered and typical ones pursued to establish an understanding of problems and advantages. No detail structural designs or loads analyses were undertaken nor were details felt to represent typical design or current engineering practice investigated further.

Emphasis throughout the study was on those elements of the spinning-stage concept that were unique in comparison to IUS/Tug design operations and interfaces. No purpose would be served by repetition of other STS data and studies.

Accuracy of the cost estimating processes was limited by the relative amount of cost data base on satellites and the level of definition in the satellite design. Similar limitations apply to the SSUS stage costing, although in this case a large IUS assessment three-axis stage cost data base existed which was applied using complexity factors to the spinning stage. However, the spin-stage options were very preliminary conceptual designs in comparison to the highly evolved IUS designs and program plans.

## SECTION 7

### SUGGESTED FUTURE EFFORTS

It is recommended that further studies of the SSUS systems be pursued if the SSUS option appears competitive with other STS upper stage options. The present study has explored the initial technical concepts of the spinning systems, but the depth of investigation and the number of options that could be evaluated were limited. The most useful future work would be in the following areas.

#### 7.1 SYSTEM STUDIES RELATING THE SSUS CONCEPT TO THE DOD SOLID PROPELLANT IUS CONCEPT SELECTION

#### 7.2 DYNAMIC STABILITY AND INJECTION ERROR ANALYSES

- a. Improved computer simulation of all error source contributions
- b. Direct solution of ground-guided AKM burn characteristics and errors
- c. Dynamic structural/control non-rigid body modeling of Spacecraft/SSUS to replace present rigid body analysis (use Fleetsatcom, DSCS II, or equivalent existing payload dynamic model)
- d. Planetary mission error analysis and mission design (consult with JPL)
- e. Non-optimum geosynchronous mission design (non-Hohmann transfer) and non-geosynchronous earth orbit injection error analyses
- f. Separation and deployment dynamic analyses to verify Orbiter safety and accuracy error sources
- g. Analysis of integral AKM (non-communication and navigation) payloads and dual-spin satellites characteristics with the SSUS concept derived in the present study or improved concepts.

### 7.3 DESIGN STUDIES

- a. Studies in detail to optimize sizing stage family for total or selected portions of mission model
- b. Studies in detail of modular structural and stage system to accept a variety of motors and deployment from common Orbiter cradle spin-table systems.
- c. Trade studies of spin-table cradle versus external spinup concepts from IUS-type cradle options and possible commonality with IUS cradle
- d. Study spin/despin characteristics/modification of a real three-axis stabilized satellite (ATS-F or equivalent) for SSUS deployment
- e. Conduct loads and stress analyses of selected cradle, spin-table, and stage designs to verify acceptability for preliminary design purposes.

### 7.4 OPERATIONS AND INTERFACES

- a. Assess the flight and ground operations aspects of the SSUS utilizing improved stage concepts and better identification of applications
- b. Prepare preliminary interface control documents between the SSUS and Orbiter and SSUS AKM and PKM to payload.